FLATIRON INSTITUTE
Center for Computational Astrophysics

Live fast and die young:

Massive, exploding, and speeding stars

Mathieu Renzo

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Collaborators: Y. Götberg, E. Zapartas, S. Justham, K. Breivik, L. van Son, R. Farmer, M. Cantiello, B. D. Metzger, D. Hendricks, C. Xin, E. Farag, S. Oey, S. de Mink, ...

M*f*A community norms

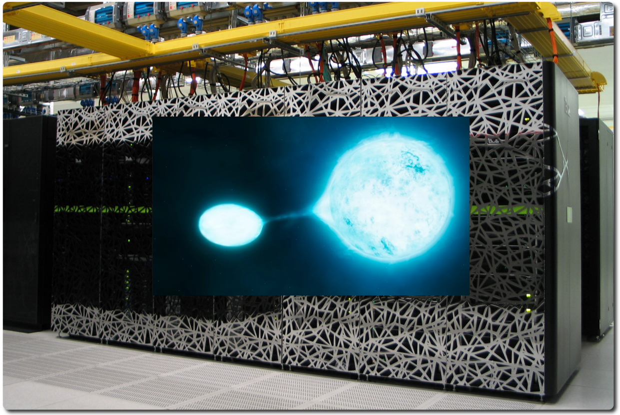
- Stay Curious – do interrupt with questions!
- Work Together/Collegiality – science is a team effort!
- Stay Fully Present (use devices only when needed)
- Actively Listen to Understand
- Invite and welcome contributions from everyone

credits: U. Shah


Santa Barbara
Amsterdam
New York
Pisa
Tucson
Empoli

I am a theoretical and computational astrophysicist

Theory +



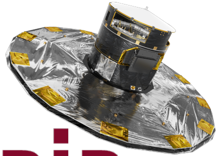
Dutch national supercomputer Cartesius

=

Numerical Simulations

My main goals today

1. Share my research
2. *Experiment* together with high-school teachers
   - Connect research, outreach, and education
   - Leverage **open science**



gaia

My main goals today

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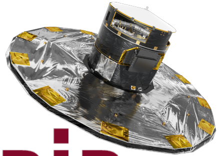
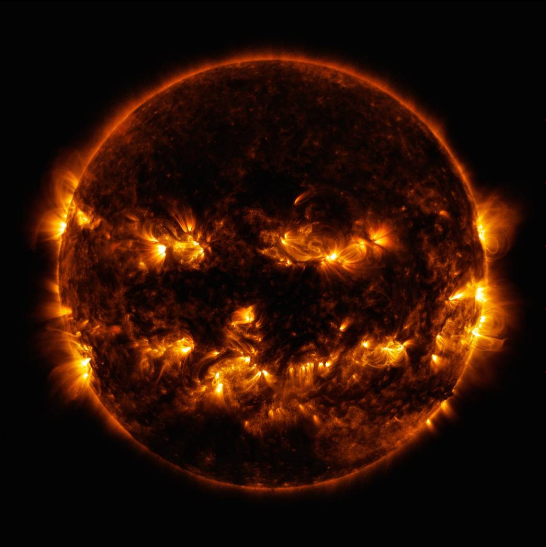
    - Connect research, outreach, and education
    - Leverage **open science**

Q. *What would you want from researchers?*



Stellar evolution quickstart

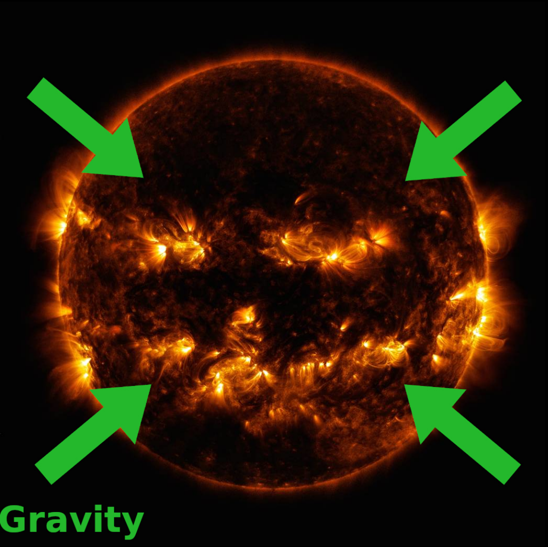
The nearest star to us is the Sun



- Current age $\sim 4.5 \cdot 10^9$ yr
- Expected lifetime $\sim 10^{10}$ yr
- $L_\odot \simeq 4 \cdot 10^{33}\,\mathrm{erg\ s^{-1}}$
- $M_\odot \simeq 2 \cdot 10^{33}\,\mathrm{g} \simeq 10^4\, M_{♃} \sim 3 \cdot 10^5\, M_\oplus$
- $R_\odot \simeq 6.95 \cdot 10^{10}$ cm

credits: NASA

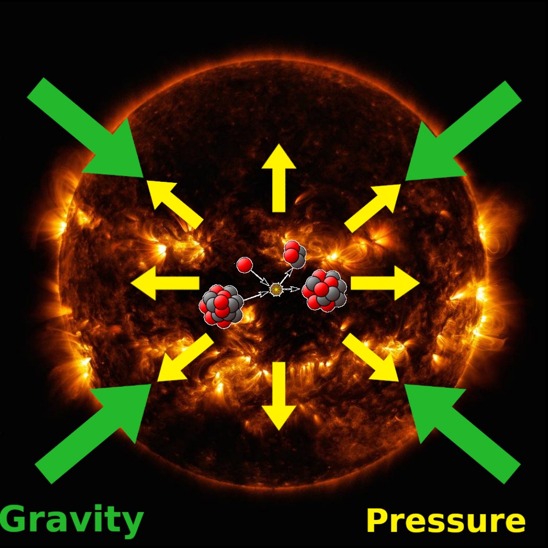
Stars are large balls of matter that “resist” their own weight



Pushing against gravity costs energy

Energy leaks as γ (and ν)

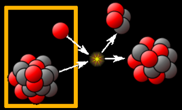
Stars produce their own energy by nuclear fusion



Pushing against gravity costs energy

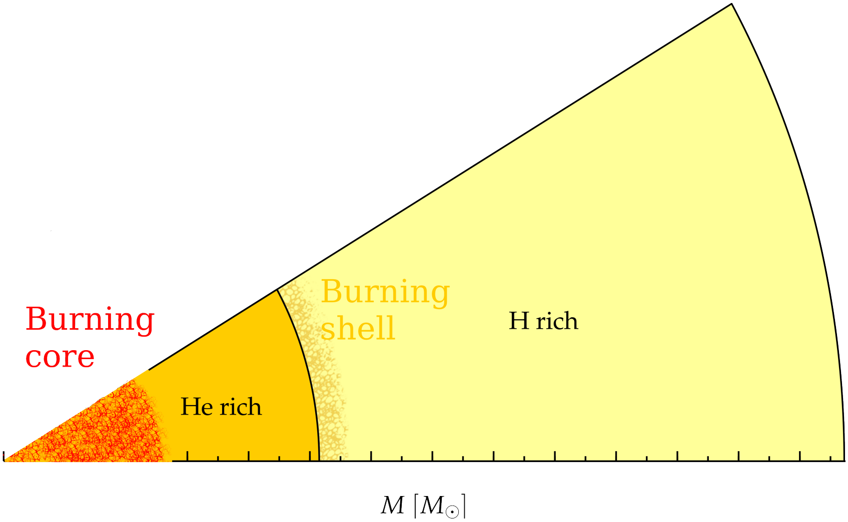
Energy leaks as γ (and ν)

To compensate, stars produce energy by **nuclear fusion**



When they run out of “fuel” and are forced to evolve

Core burns heavier fuel, shells burn the leftovers



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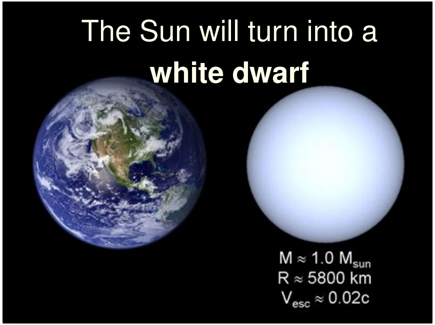
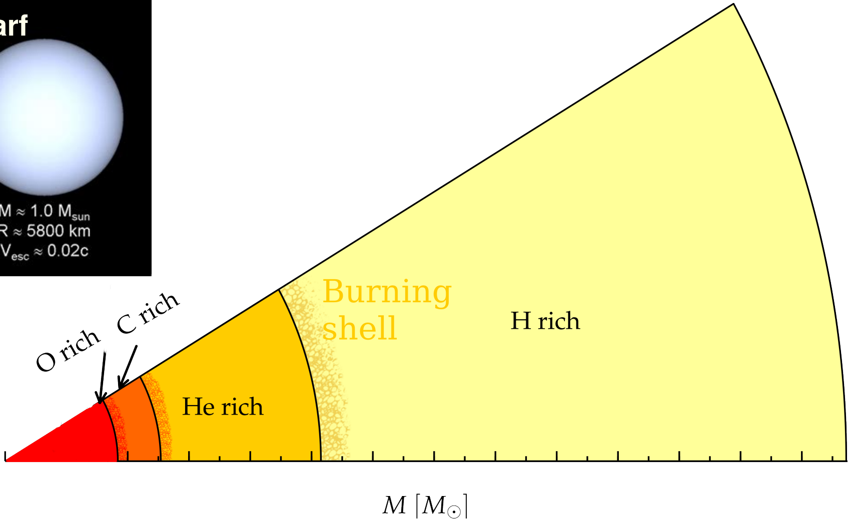
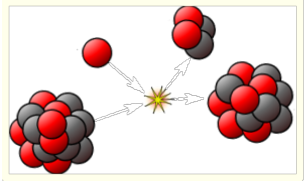


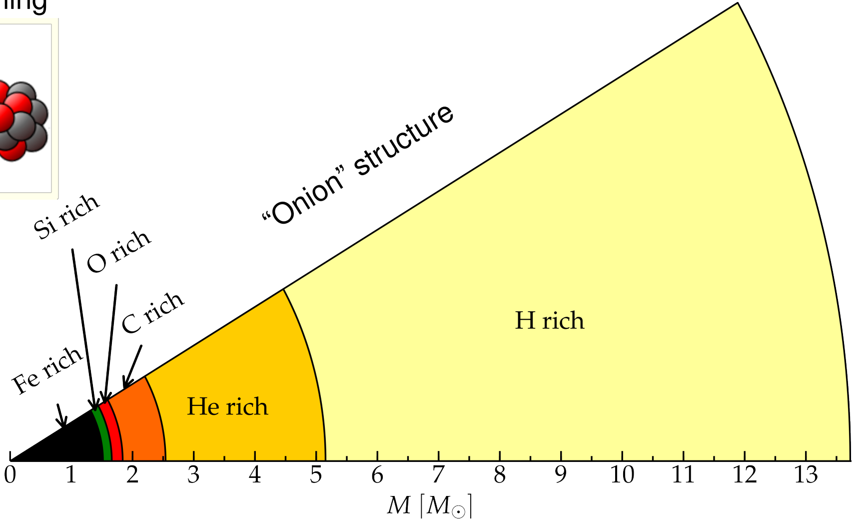


Massive stars burn until Iron, then gravity wins

Fusion of Iron **costs** energy:

the star stops burning





Renzo 2015

Supernova explosion: the birth Neutron Stars or Black Holes

Credits: Kuo-Chuan Pan

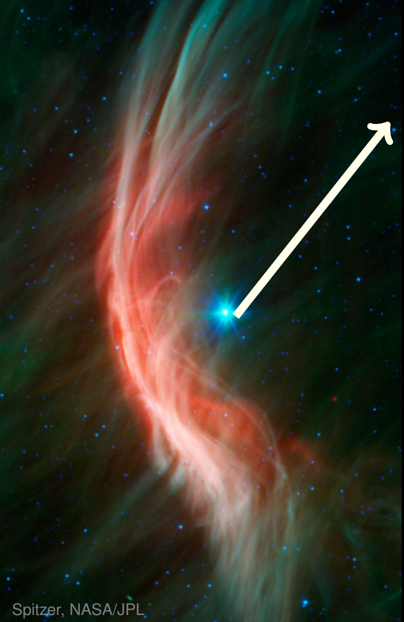
https://www.youtube.com/watch?v=bxKwMGgAkc

Why massive stars? ($M_{\text{initial}} \gtrsim 7.5\,M_\odot$)

Spitzer, NASA/JPL

ζ Ophiuchi is the nearest massive star to Earth

They are the progenitors of neutron stars & black holes



Spitzer, NASA/JPL

NS, BH

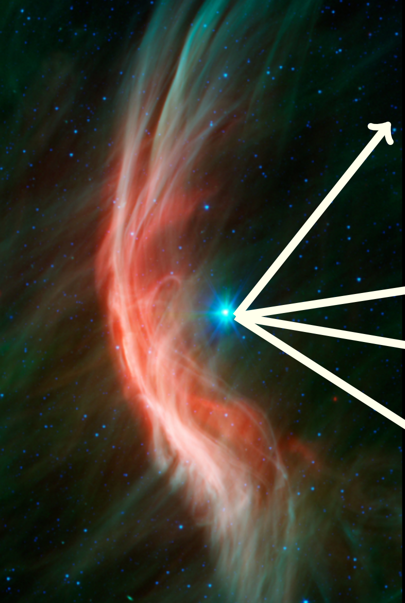
&

gravitational waves

EM:
O'Connor & Ott 2011, Ertl *et al.* 2016, 2020, Farmer *et al.* 2016, Morozova *et al.* 2015, 2016, Renzo *et al.* 2017, 2020a, b, c, Laplace *et al.* 2021, Vartanyan *et al.* 2021, Zapartas *et al.* 2017a, 2019, 2021a, b, Marchant *et al.* 2019, Farmer *et al.* 2019, 2020

GW:
LVK collaboration 2015-23, Vigna-Gómez *et al.* 2018, van Son *et al.* 2020, 2021, Callister, Renzo, Farr 2021, Renzo *et al.* 2021

They shape their environment & the Universe as a whole



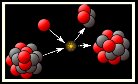
Spitzer, NASA/JPL

NS, BH
&
gravitational waves

Stellar feedback

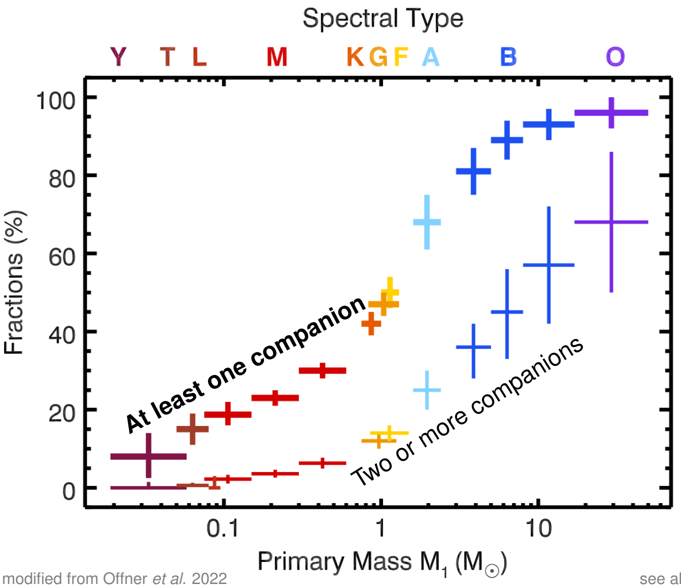
Ionizing radiation

Star Formation
& cluster evolution



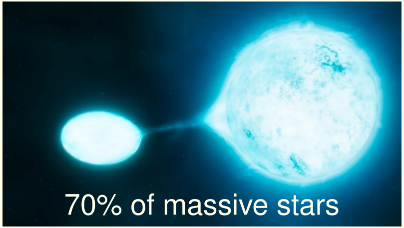
Nucleosynthesis &
chemical evolution

Most massive stars are born with companion(s)



modified from Offner *et al.* 2022

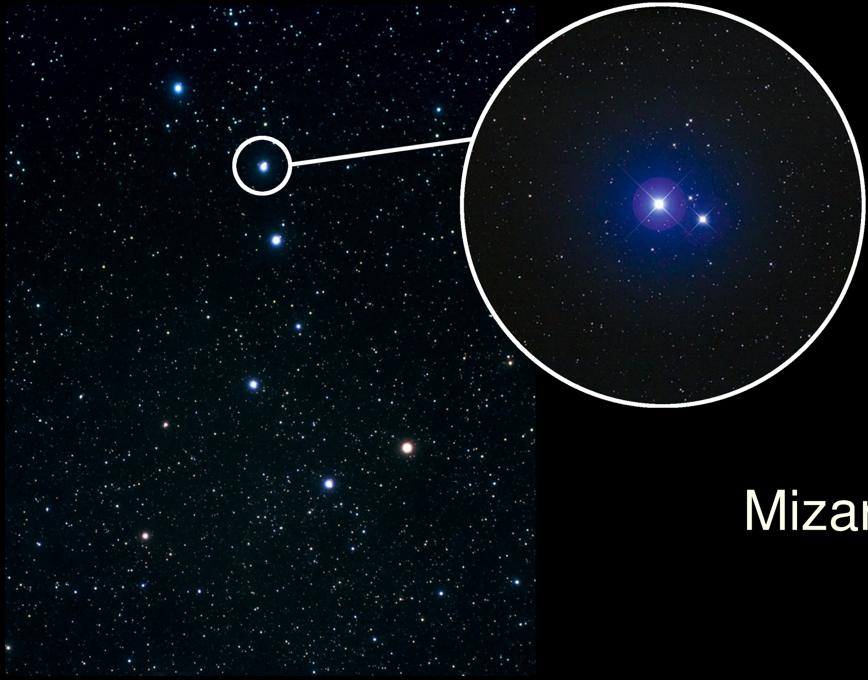
Binary interactions are common



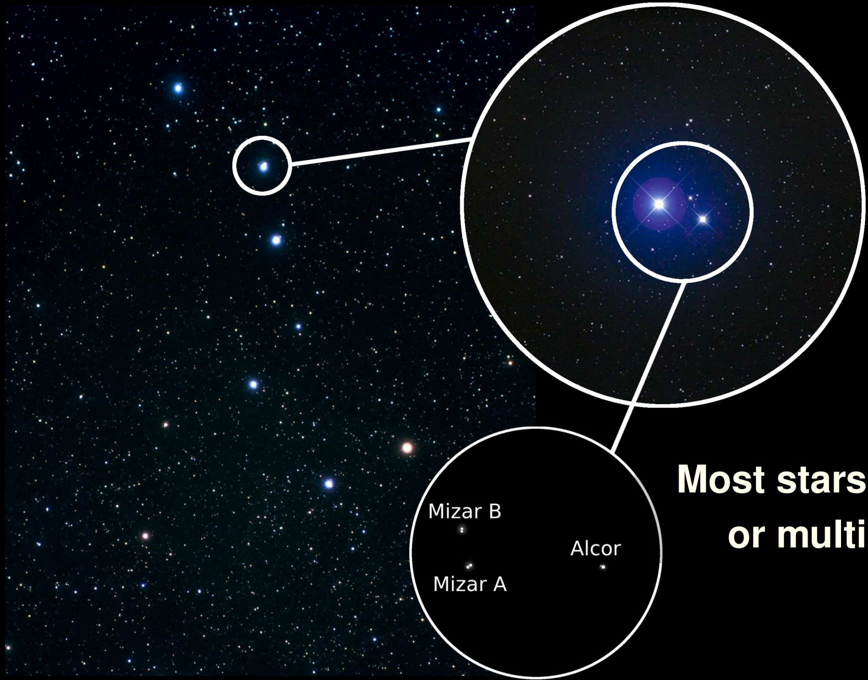
Sana *et al.* 2012

see also Mason *et al.* 2010, Kobulnicky & Fryer 2007, Moe & di Stefano 2017

The big dipper

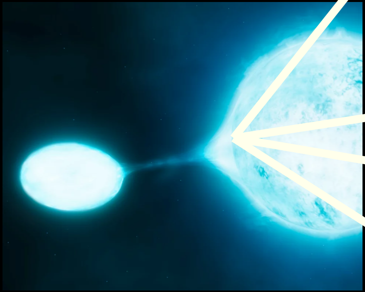


Mizar & Alcor



Most stars are in binaries or multiple systems

Binary interactions *change* massive star feedback



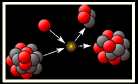
ESO, L. Calçada, M. Kornmesser, S.E. de Mink

Stellar feedback

NS, BH
&
gravitational waves

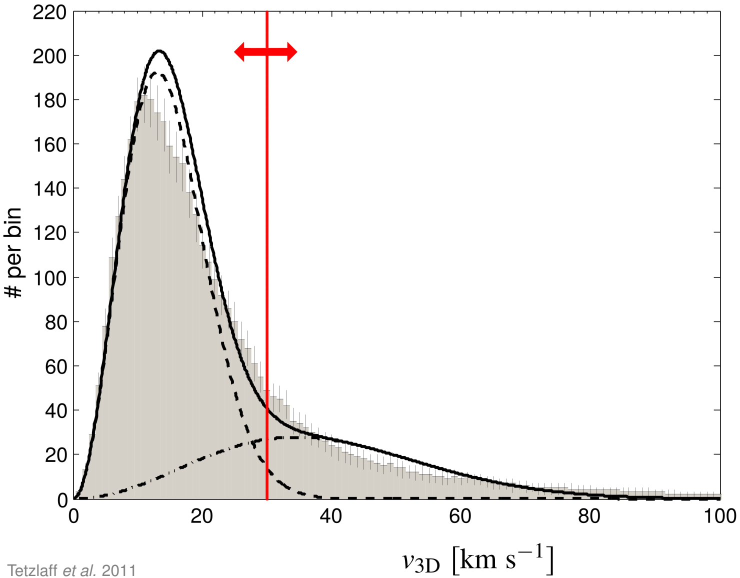
Ionizing radiation

Star Formation
& cluster evolution



Nucleosynthesis &
chemical evolution

Stars move through their host galaxy: peculiar motion on top of orbit



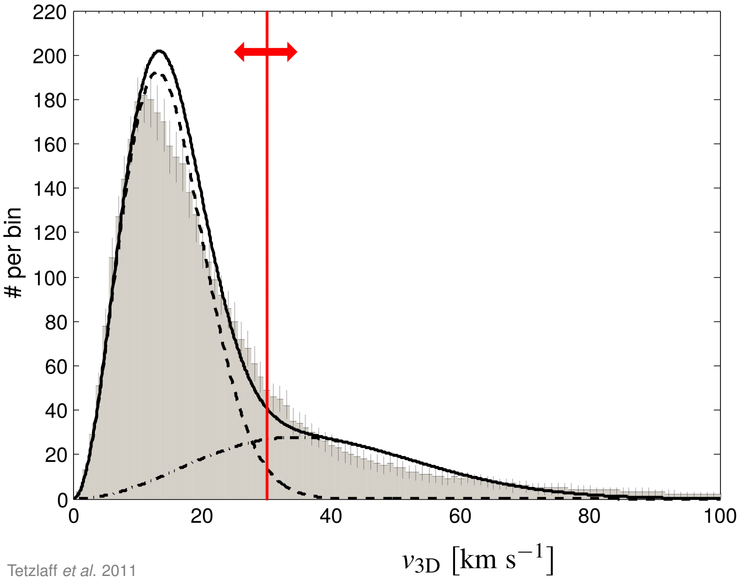
Tetzlaff *et al.* 2011

Runaways are the tail

Typically have fewer companions

Blaauw 61

Runaway stars are common among massive stars



Tetzlaff *et al.* 2011

Runaways are the tail

Typically have fewer companions

Blaauw 61

Observed fraction

$$M \gtrsim 15\,M_\odot,\ \sim 10-20\%$$

How to measure stellar velocities ?

How to measure stellar velocities

"Bow shock"

$v > c_s$

$\Leftarrow$ Special features

(if relatively nearby)

"Bow wave"

$v_{\mathrm{boat}} > v_{\mathrm{wave}}$

How to measure stellar velocities

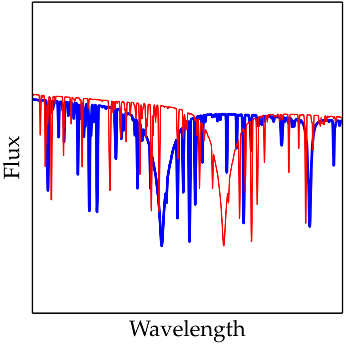
$\Leftarrow$ Special features

(if relatively nearby)

Radial velocities

(Doppler shift)

$\Rightarrow$



Credits: Pink Floyd

How to measure stellar velocities

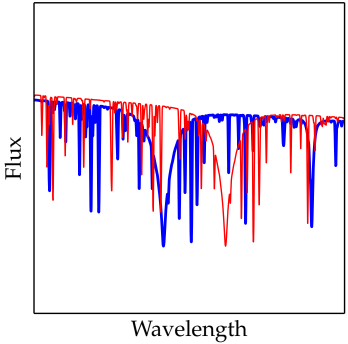
⇐ Special features

(if relatively nearby)

Radial velocities

(Doppler shift)

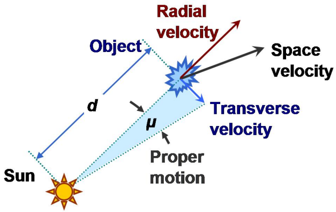
⇒



Proper motions

(if distance known)

⇓



Measuring distances is one of the most difficult things in astrophysics

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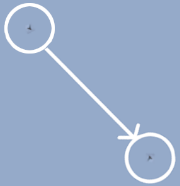
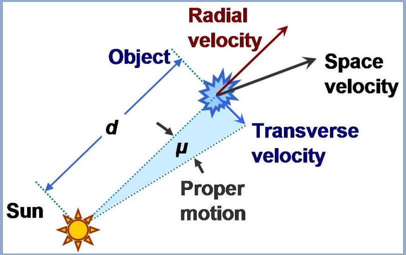
Angular velocity + parallax = projected physical velocity



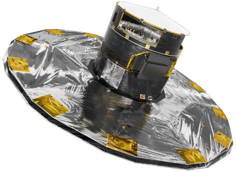


A “renaissance” of stellar physics

driven by the *Gaia* space-telescope

Gaia scans the sky to measure d and v of 10s of billions of stars

https://flathub.flatironinstitute.org/gaiadr3



gaia

- Distance ↔ parallax
- Velocities ↔ pm and RV

$\Downarrow$

Enables lots of astrophysics

Credits: New Scientist/ESA

https://www.youtube.com/watch?v=BT0Xh1BizSI

Apparent motion

reflection of Earth's orbit around the Sun

https://www.youtube.com/watch?v=0-jhyRIupY4

Long term drift

Stars' orbit around Galaxy + intrinsic motion

https://www.youtube.com/watch?v=cEsfqFDSpm0

Gaia requires multiple years of observations

Mission Elapsed Time 09:05:11:05:55:38

YRS MOS DAYS HRS MINS SECS

Why some star “run”?

- Binary SuperNova Scenario (BSN)
- Dynamical Ejection Scenario (DES)

BSN: the most common massive binary evolution path

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink — `https://www.youtube.com/watch?v=pDDjEkGjV9U`

Mass transfer occurs before the 1^{st} explosion

- **Spin-up**

  Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013, Renzo & Götberg 2021

- **Pollution**

  Blaauw 1993, Renzo & Götberg 2021

- **Rejuvenation**

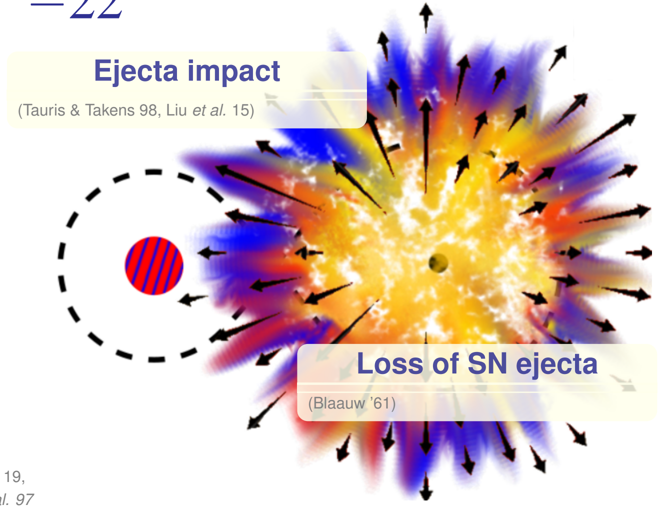
  Hellings 1983, 1985, Renzo *et al.* 2023

The “widowed” star carries signatures of its past in a binary

Renzo & Zapartas 2020

What exactly disrupts the binary?

$86^{+11}_{-22}\%$ of massive binaries are disrupted



Renzo *et al.* 19b, Kochanek *et al.* 19,
Eldridge *et al.* 11, De Donder *et al. 97*

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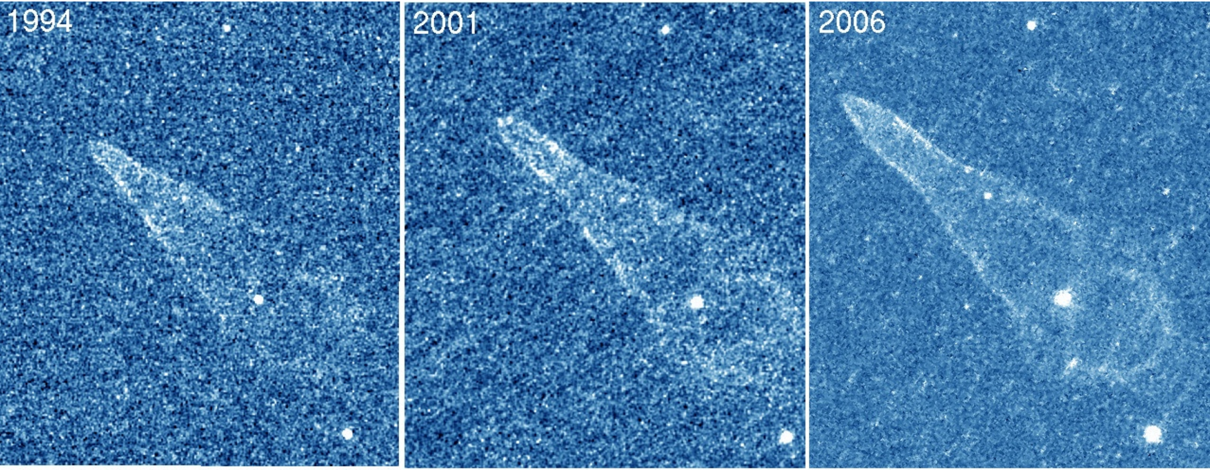
Why kicks? Neutron stars are usually faster than their progenitor stars

HST



"Guitar nebula": $v_{\rm NS} \simeq 1000\,{\rm km\,s^{-1}}$

Cordes *et al.* 1993, Chatterjee & Cordes 2004, de Vries *et al.* 2022

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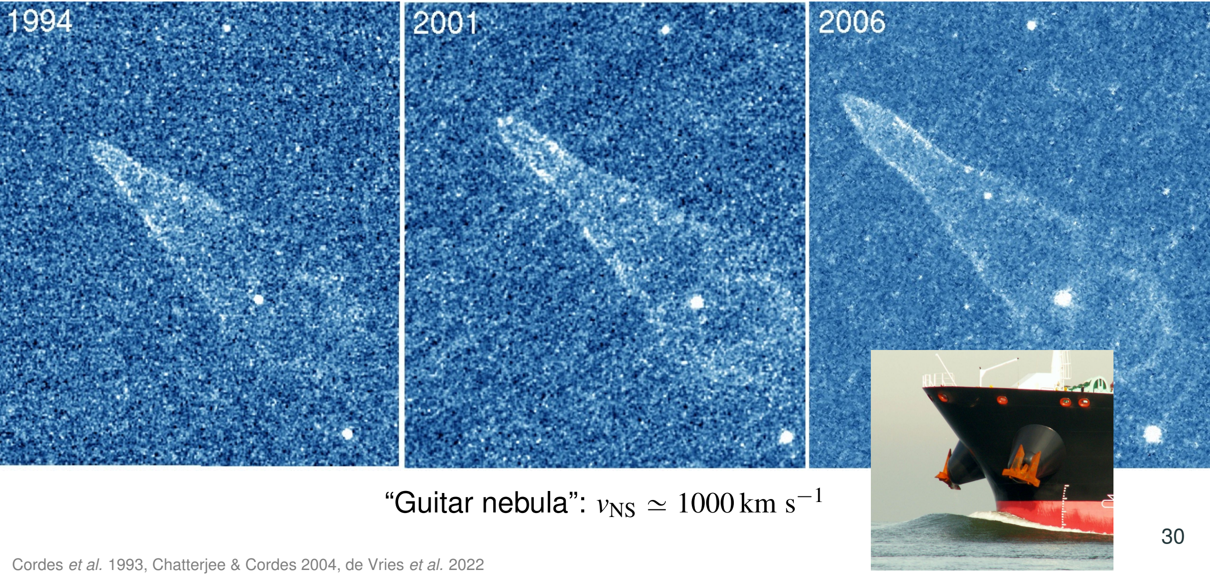


“Guitar nebula”: $v_{\rm NS} \simeq 1000\,{\rm km\ s^{-1}}$

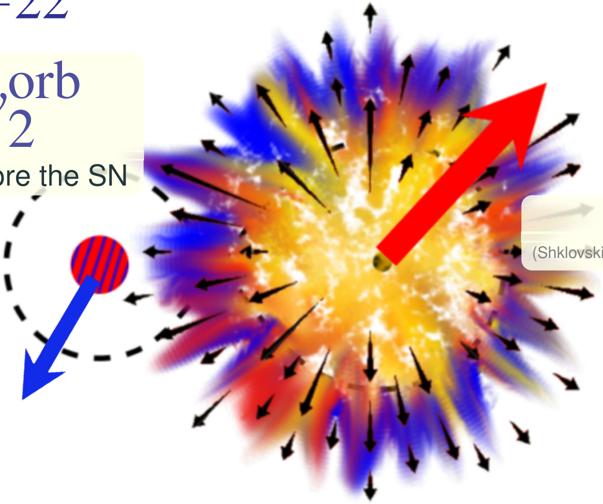
Cordes *et al.* 1993, Chatterjee & Cordes 2004, de Vries *et al.* 2022

Kicks do not change companion velocity

$86^{+11}_{-22}\%$ of massive binaries are disrupted

$$v_{\mathrm{dis}} \simeq v_2^{\mathrm{orb}}$$

before the SN

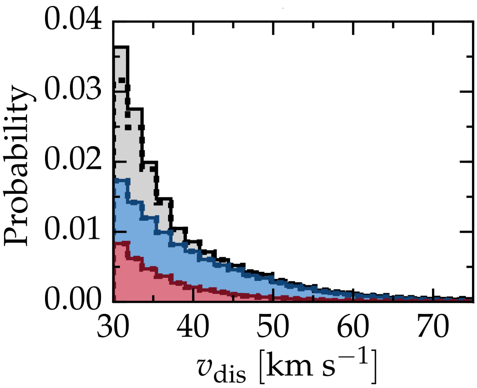


SN Natal kick

(Shklovskii 70, Katz 75, Janka 13, 17)

Renzo *et al.* 19b, Kochanek *et al.* 19,
Eldridge *et al.* 11, De Donder *et al. 97*

Accretor stars can be *runaways*...

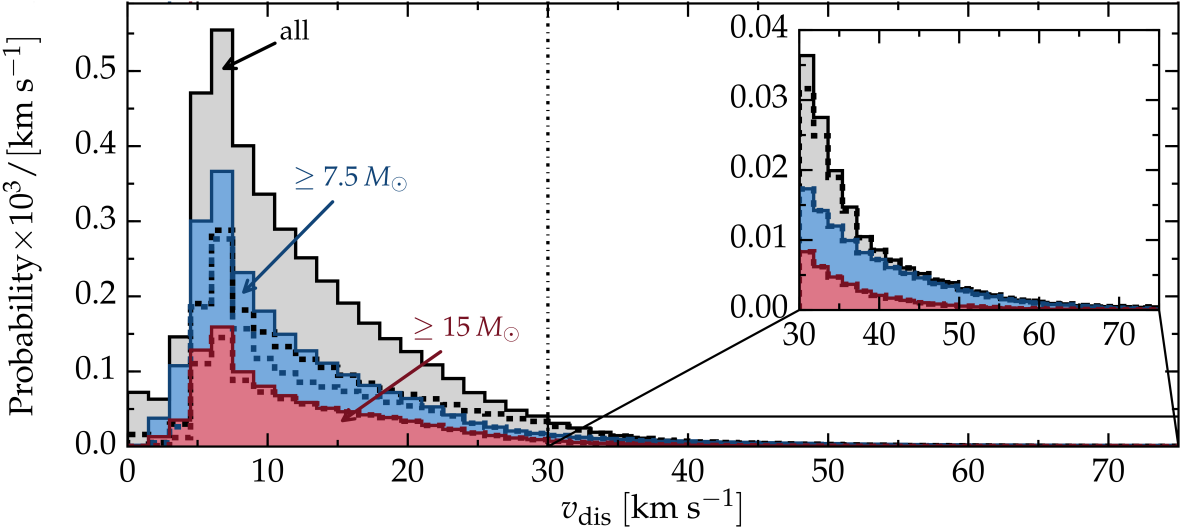


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

...but most are only *walkaways*



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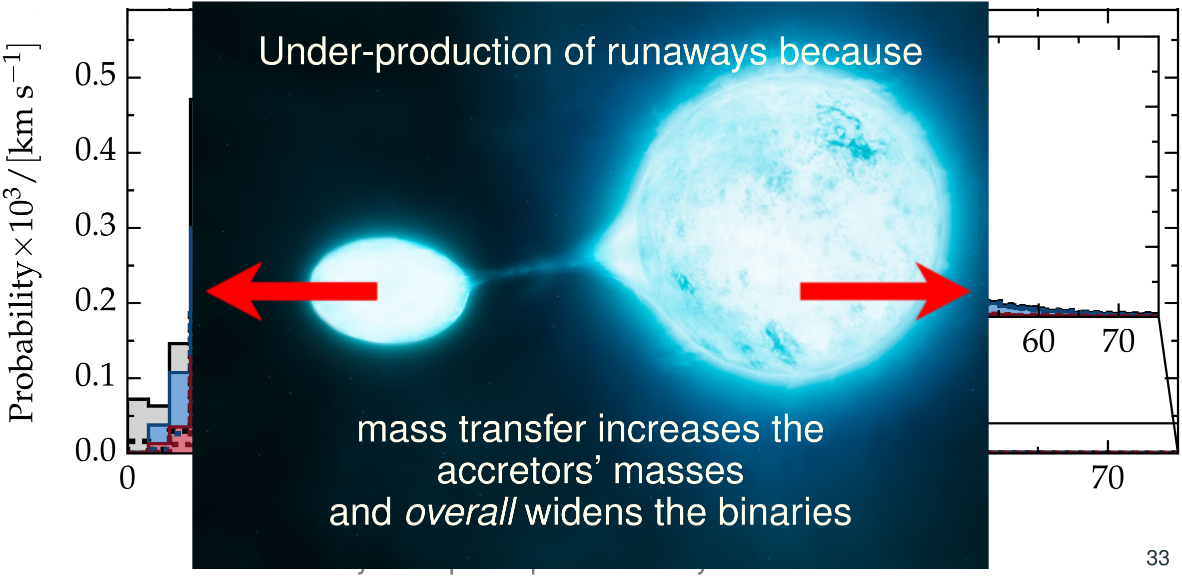

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Constrain BSN with the nearest massive star to Earth

Spitzer, NASA/JPL

Walker *et al.* 1979,
Herrero *et al.* 1994,
van Rensbergen *et al.* 1996,
Hoogerwerf *et al.* 2001,
Villamariz & Herrero 2005,
Walker & Koushnik 2005,
Zee *et al.* 2018,
Gordon *et al.* 2018,
Neuhäuser *et al.* 2019, 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

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Neuhäuser *et al.* 2019, 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

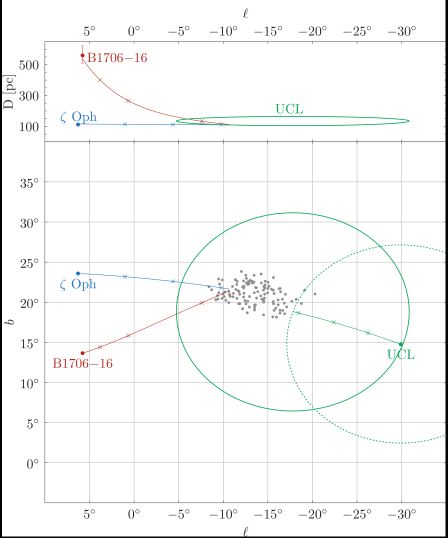
Observational constraints of ζ Oph.:

- distance $\simeq 107 \pm 4\,\mathrm{pc}$
- total mass $\simeq 20\,M_\odot$
- speed $\gtrsim 30\,\mathrm{km\ s^{-1}}$
- rotation $v\sin(i) \gtrsim 310$
- inclination $i \gtrsim 56^\circ$
- “looks” (T_eff, L)
- age $\simeq$ 8 Myr
- strange surface composition

✗ **Rotating single stars**

(e.g., van Rensbergen *et al.* 96, Howarth & Smith 01, Villamariz & Herrero 05)

ζ Ophiuchi is single but we can trace it back to a neutron star



Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

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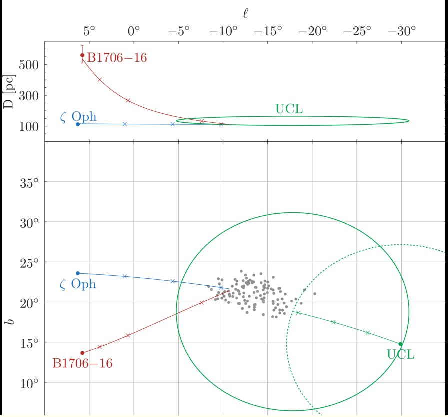


SN explosion $\sim 1.78 \pm 0.21$ **Myr ago**

$\Rightarrow$Radioactive iron rain on Earth

Benitez *et al.* 2002, Fry *et al.* 2016, Neuhäuser *et al.* 2020

Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

Why some star “run”?

- Binary SuperNova Scenario (BSN)
- Dynamical Ejection Scenario (DES)

Most stars are born in dense environments

JWST view of R136 in the LMC

Most stars are born in dense environments

N-body interactions

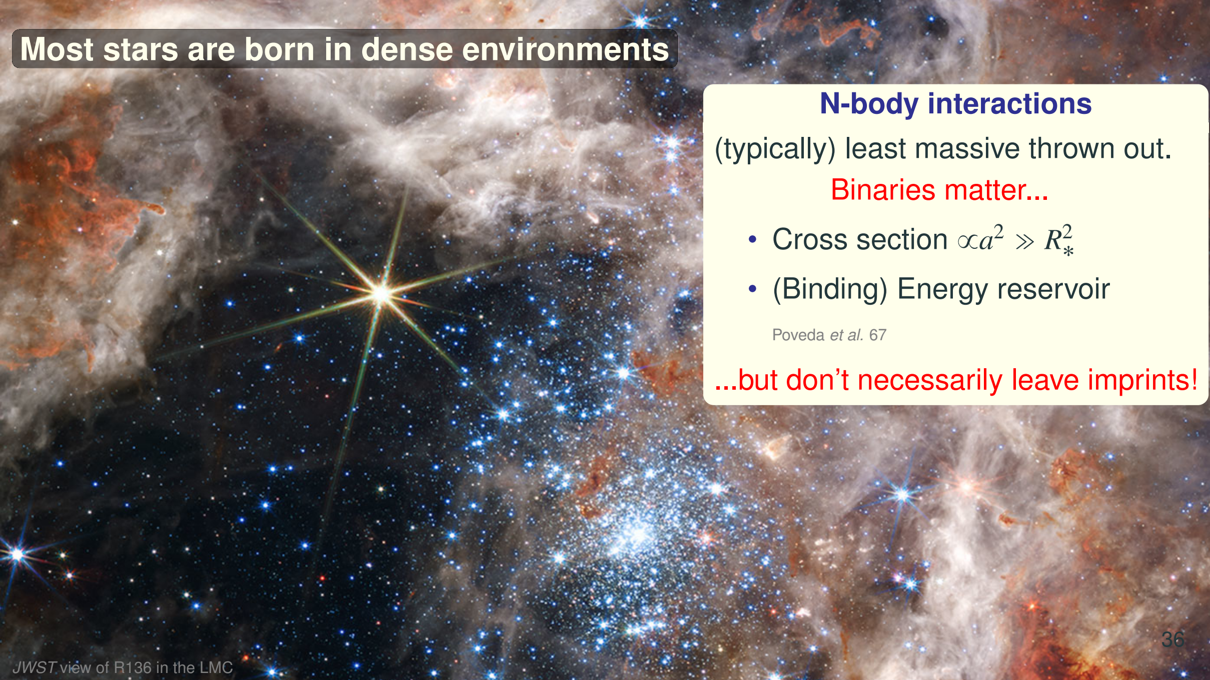
(typically) least massive thrown out.

Binaries matter...

- Cross section $\propto a^2 \gg R_*^2$
- (Binding) Energy reservoir

Poveda *et al.* 67

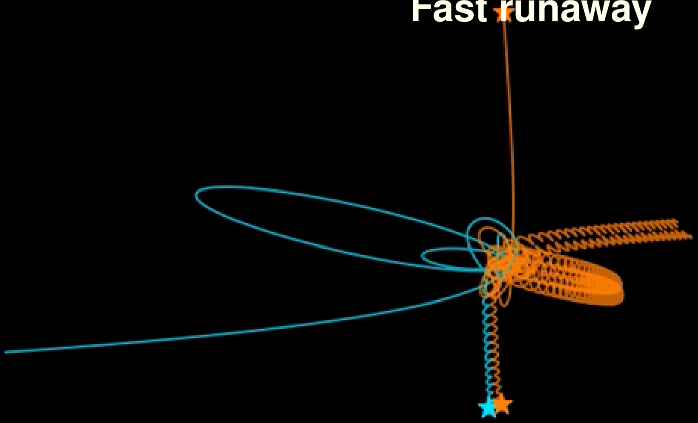
...but don't necessarily leave imprints!



JWST view of R136 in the LMC

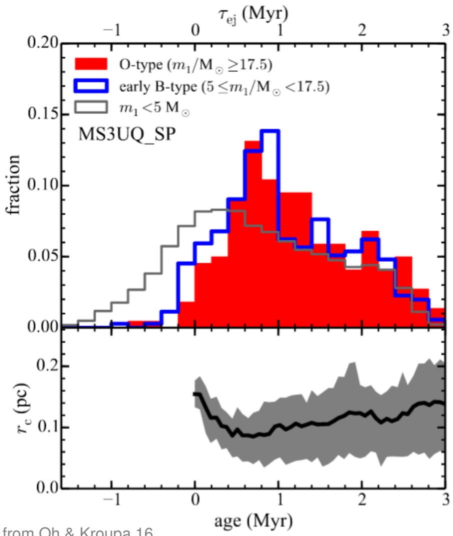
DES: typically eject the lowest mass star

Typical outcome of dynamical interactions



e.g., Fujii & Portegies-Zwart 11

Timing of ejection



from Oh & Kroupa 16,

Most ejections happen early

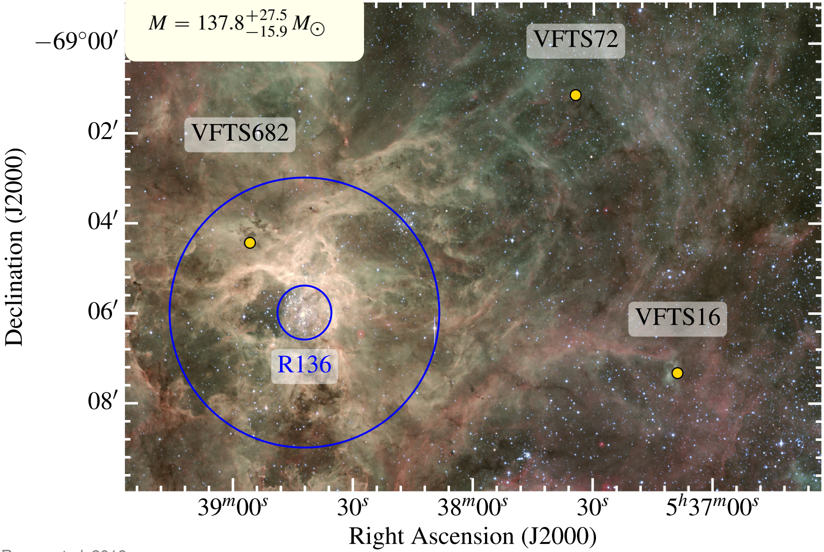
Before the first stellar death

$$\tau_{ej} < \tau_*$$

Very sensitive to initial conditions

see also, Poveda *et al.* 64, Fujii & Portegies-Zwart 11, Banerjee *et al.* 12, 14

The most massive runaways known



$M = 137.8^{+27.5}_{-15.9}\,M_\odot$

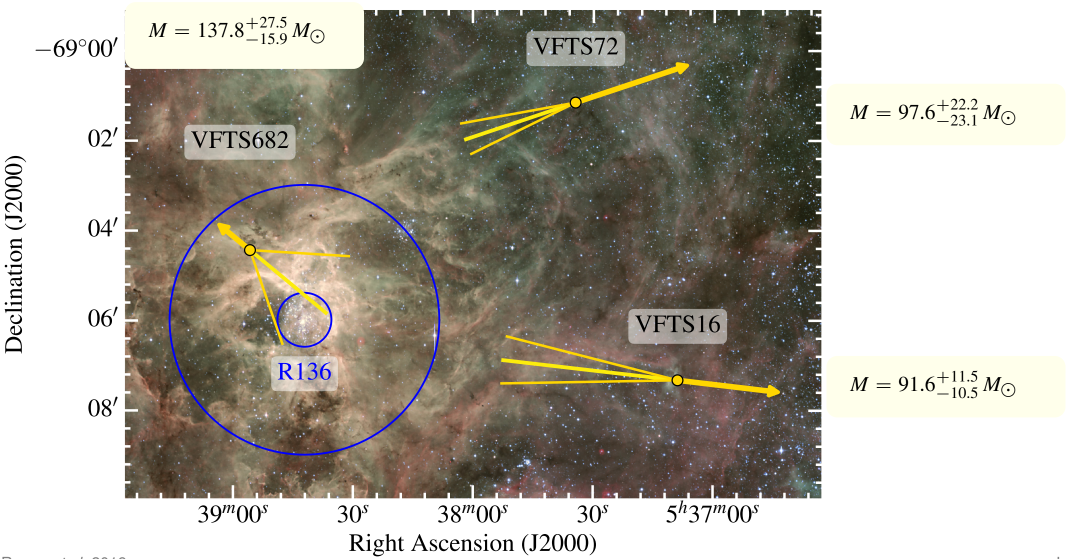
$M = 97.6^{+22.2}_{-23.1}\,M_\odot$

$M = 91.6^{+11.5}_{-10.5}\,M_\odot$

Renzo *et al.* 2019a

Lennon *et al.*, 2018

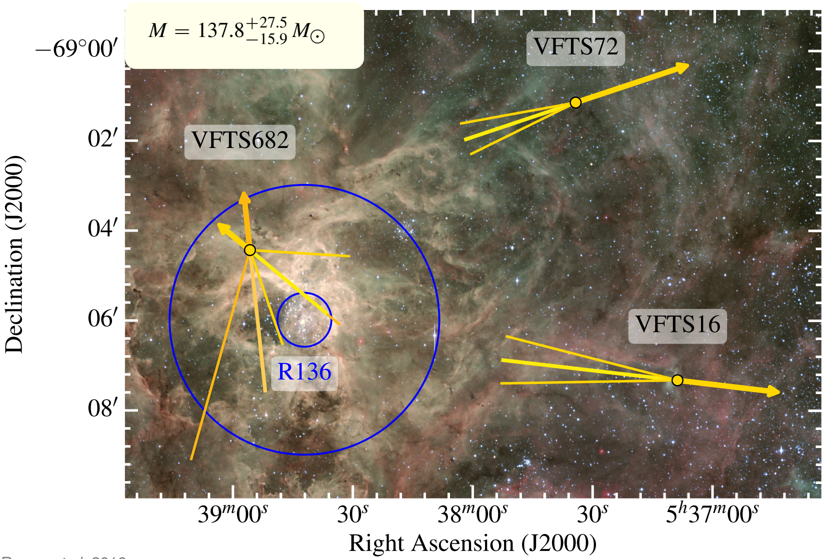
The most massive runaways known



Renzo *et al.* 2019a

Lennon *et al.*, 2018

The most massive runaways known



$M = 97.6^{+22.2}_{-23.1}\,M_{\odot}$

$v_{2D} = 93 \pm 15\,\mathrm{km\,s^{-1}}$

$M = 91.6^{+11.5}_{-10.5}\,M_{\odot}$

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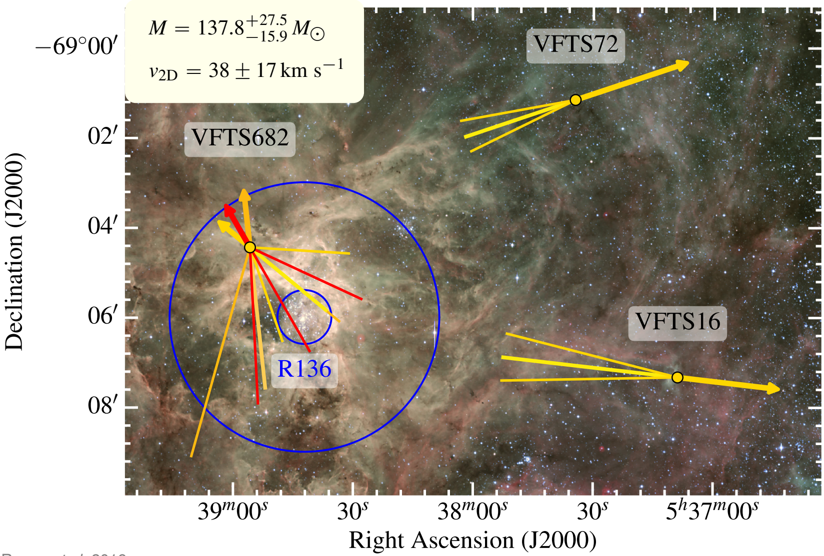

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Summary of ejection mechanisms

Dynamical ejections

- Happen before SNe
- Can produce higher velocities
- Least massive thrown out
- *Gaia* hint: high efficiency

...Binaries are still important! but might not leave signature

Binary SN disruption

- Most binaries are disrupted
- Determined by SN kick
- Ejects accretor
- $v \simeq v_2^{\rm orb}$ typically slow
- Leaves binary signature

  spin up, pollution, rejuvenation

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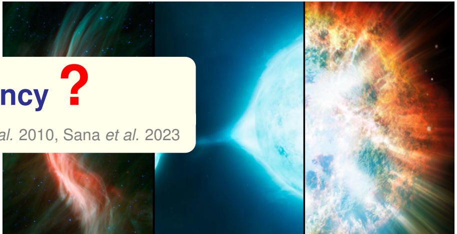
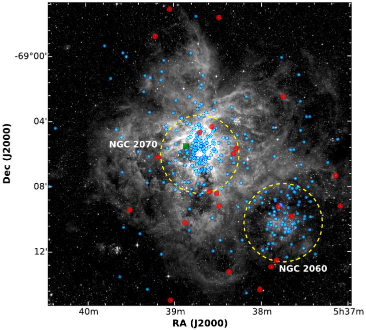


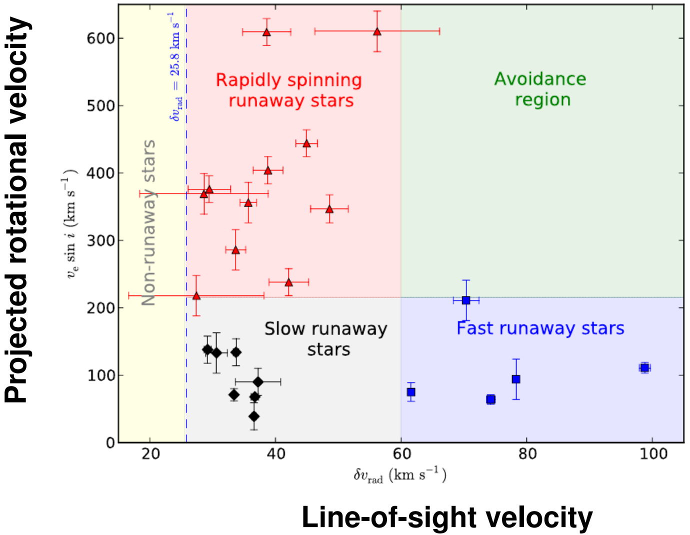
Relative efficiency ?

Hoogerwerf *et al.* 2001, Jilinksi *et al.* 2010, Sana *et al.* 2023

Both mechanism at play in the same population



(30 Doradus region of LMC)



Sana *et al.* 2023

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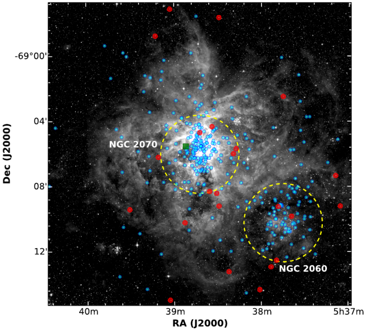

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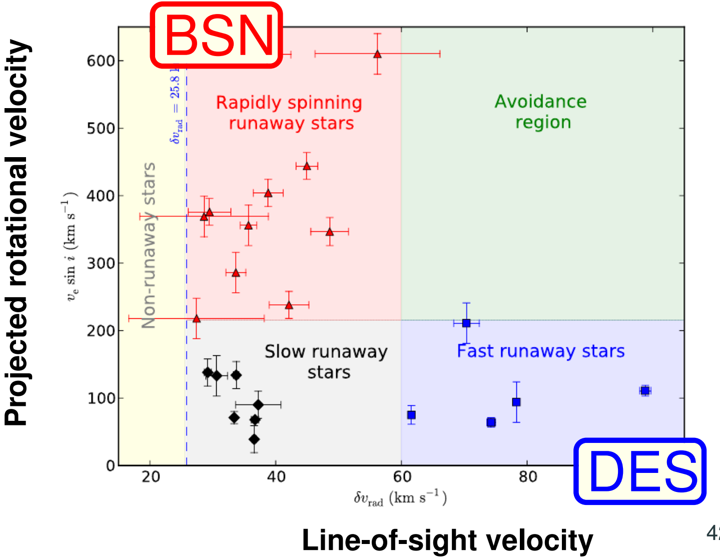
General conclusion

or

lucky age of 30 Doradus ?



Sana *et al.* 2023

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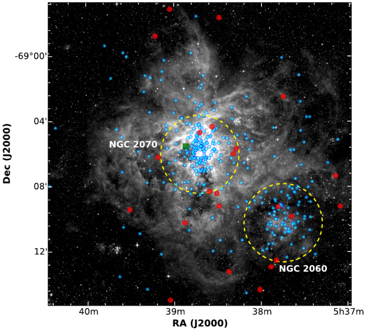

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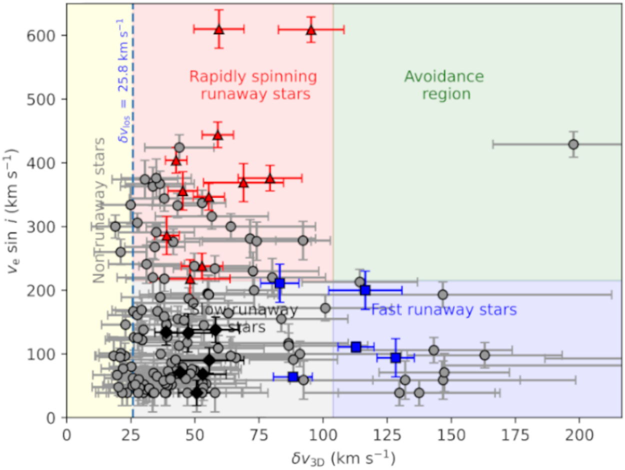
Projected rotational velocity



3D velocity

Sana *et al.* 2023

Conclusions

Gaia “renaissance” of stellar physics ⇒ wide implications for astro

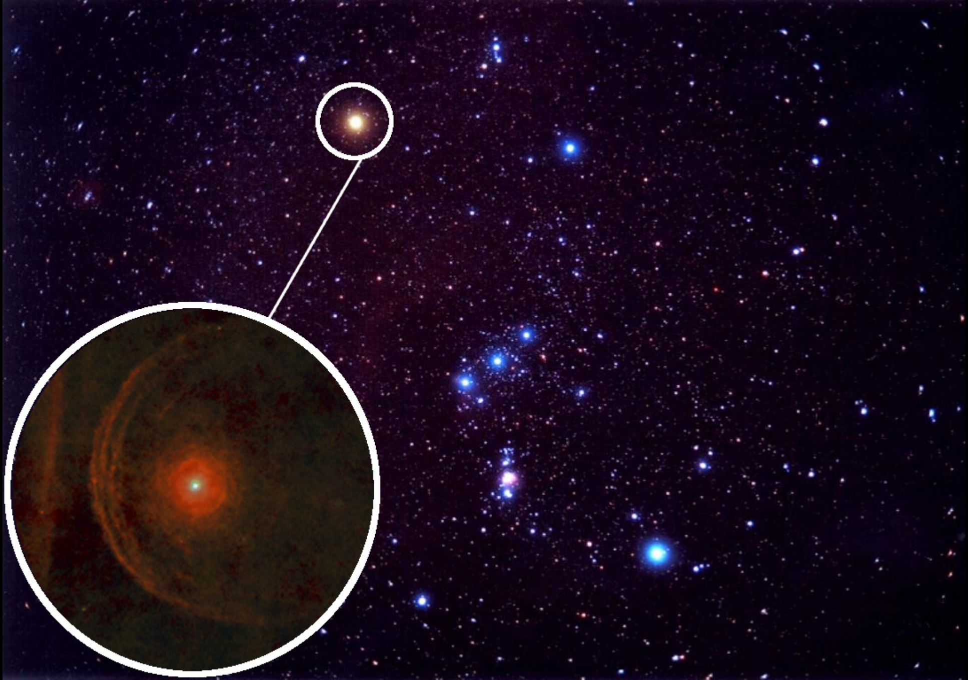
Runaways: many massive stars are fast $v \gtrsim 30\,\mathrm{km\ s^{-1}}$

Two mechanisms for $v \lesssim$ hundreds of $\mathrm{km\ s^{-1}}$:

- **BSN** Supernova explosion in a binary
- **DES** Dynamical ejection from clusters

www.youtube.com/watch?v=jKWQmbB5EQE

Orion



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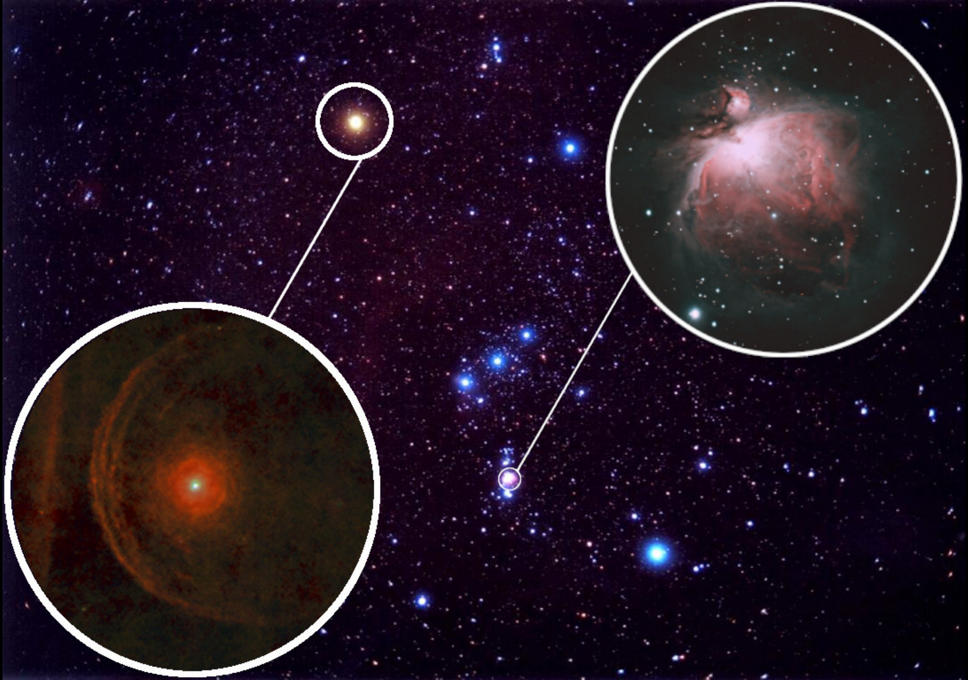

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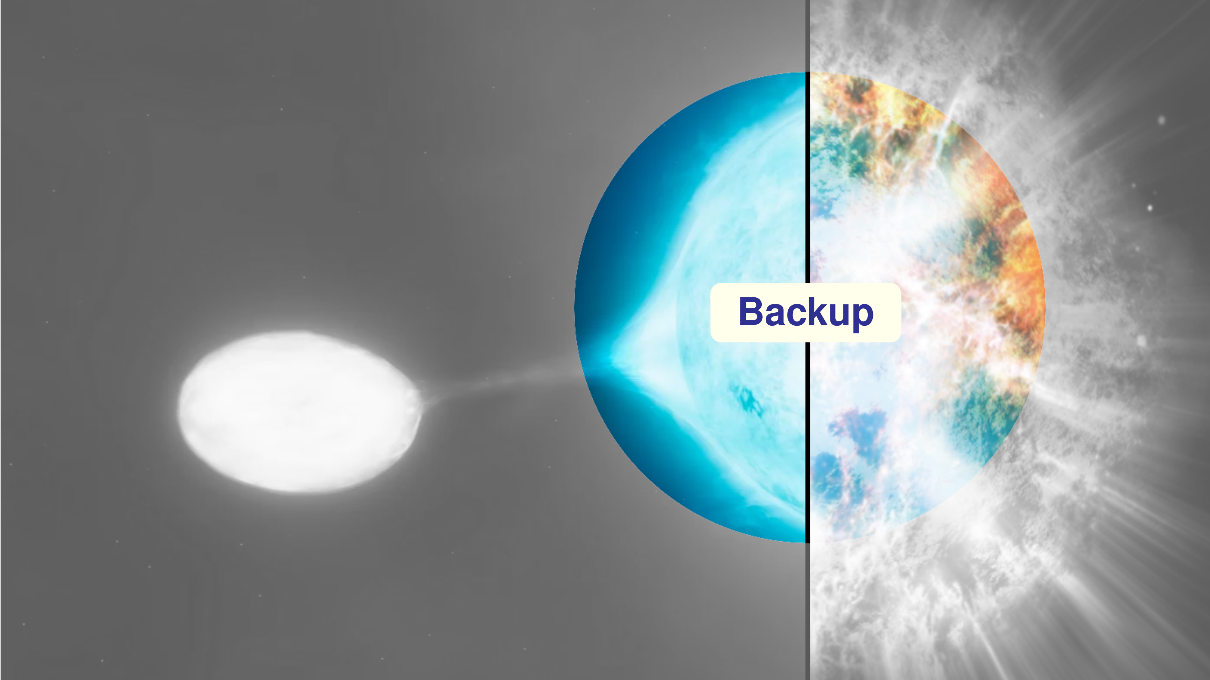
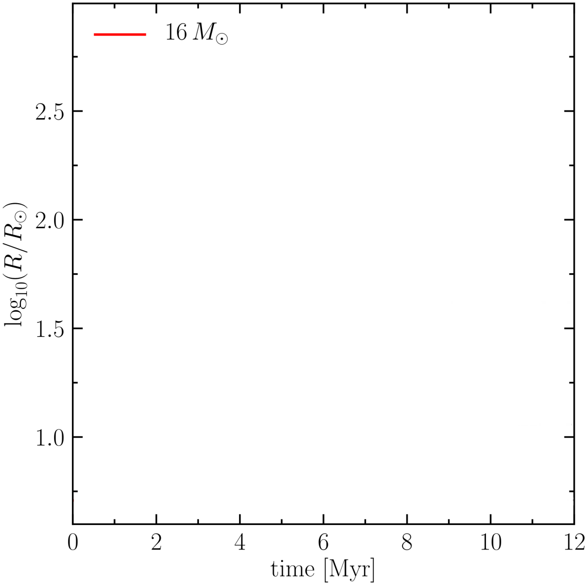
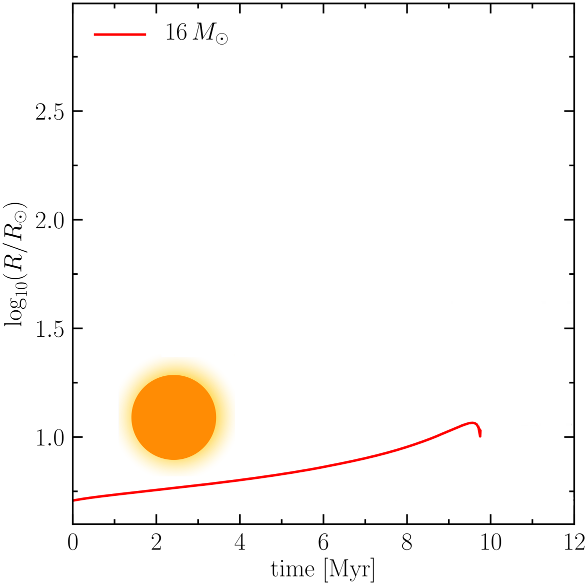

Backup

Stars are like people: they get bigger as they grow



Simulation output from

Stars are like people: they get bigger as they grow



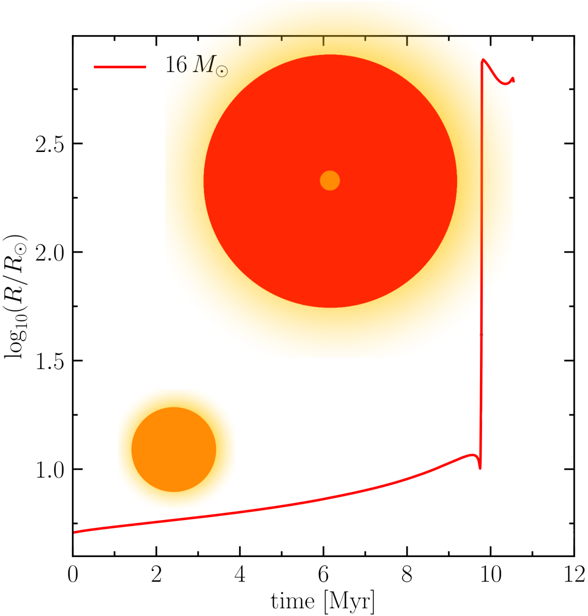
Main sequence:

H→ He, 90% of stellar lifetime

Simulation output from

MESA

Stars are like people: they get bigger as they grow



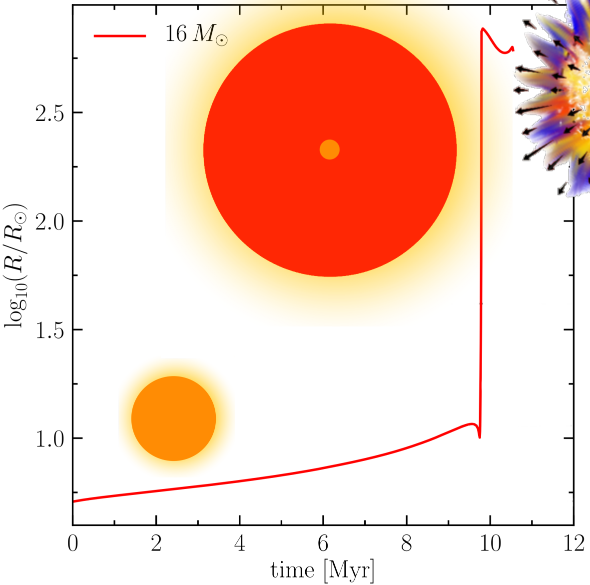
Red (super) giant:

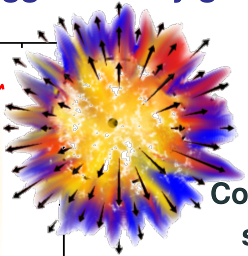
Core+shell burning, 10% of stellar lifetime

Simulation output from

MESA

Stars are like people: they get bigger as they grow





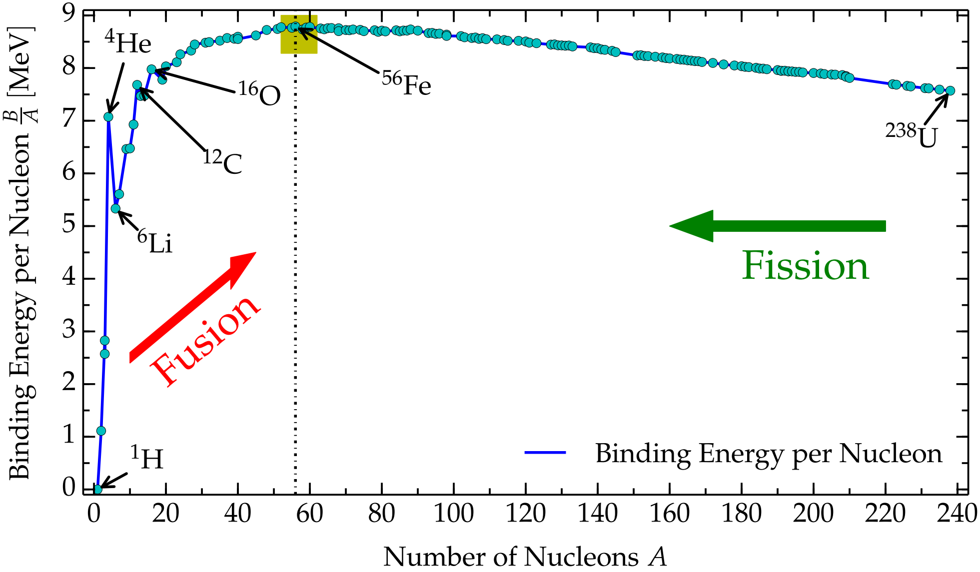
Core collapse and possibly **supernova explosion**:

$$\tau(M) \propto M^{-\alpha} \simeq 3 - 50\,\mathrm{Myr}$$

for $M \gtrsim 7.5\,M_\odot$, e.g., Zapartas et al. 2017

Simulation output from MESA

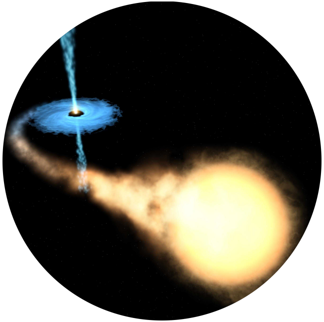
Nuclear specific binding energy



Do BHs receive kicks?

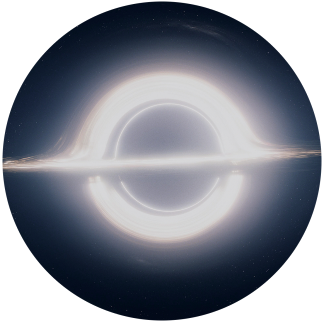
NO

⇒ most remain bound to companion



YES

⇒ most are single and we can't see them...



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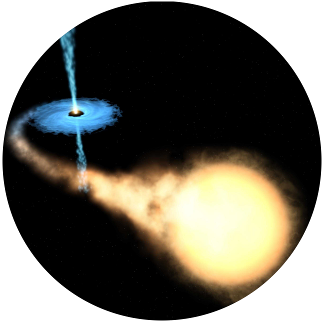

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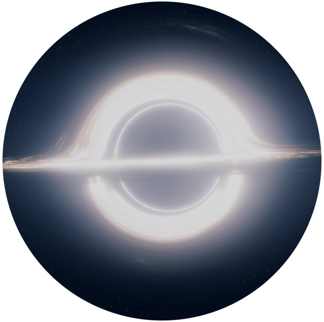
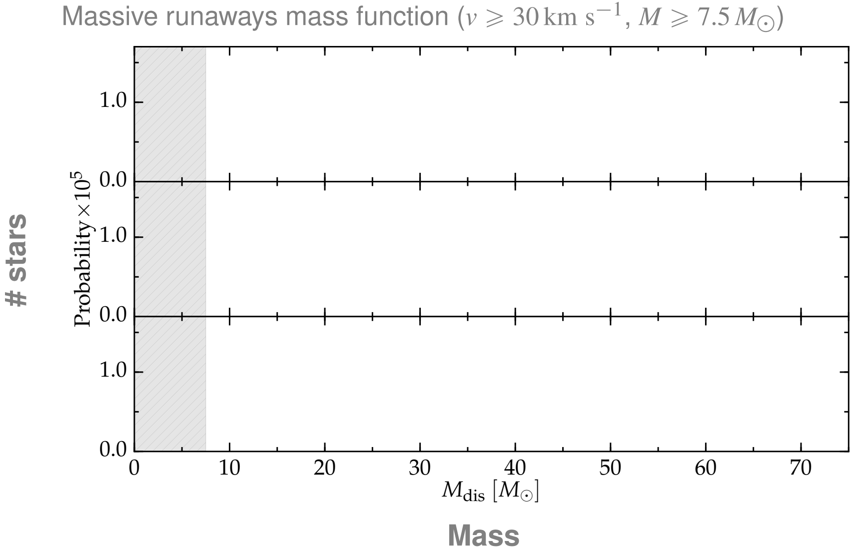


...but we can see the "widowed" companions

BH kicks by weighting the companions

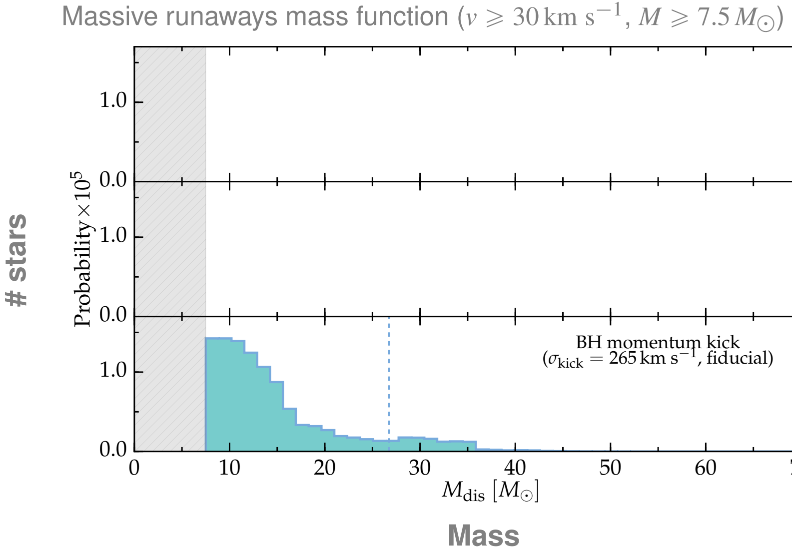


Numerical results publicly available at::

http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

BH kicks by weighting the companions



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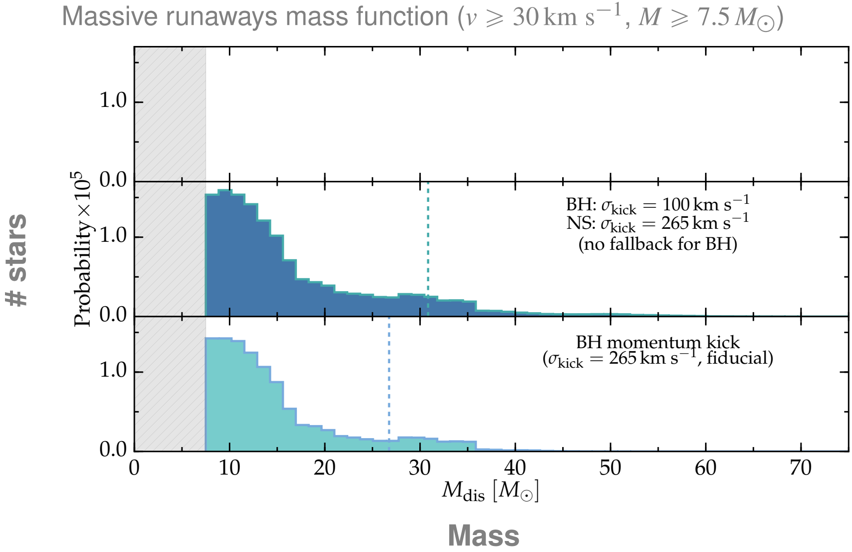

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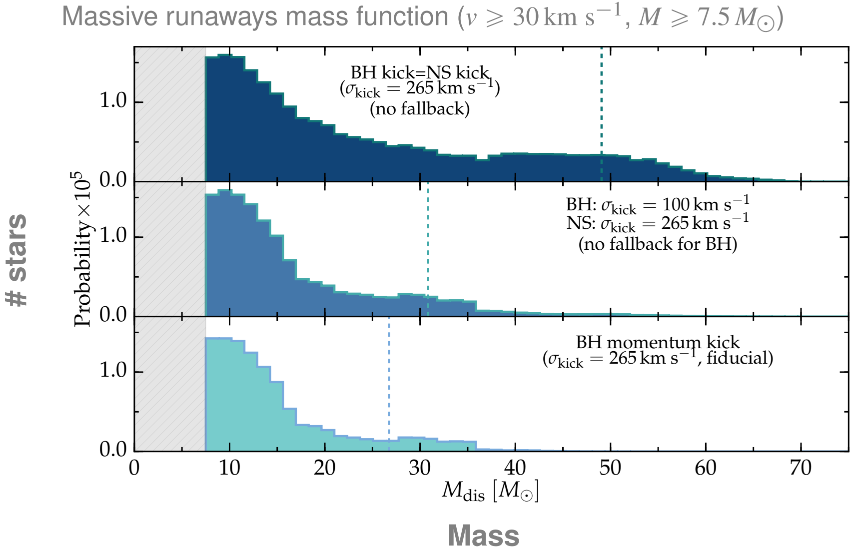

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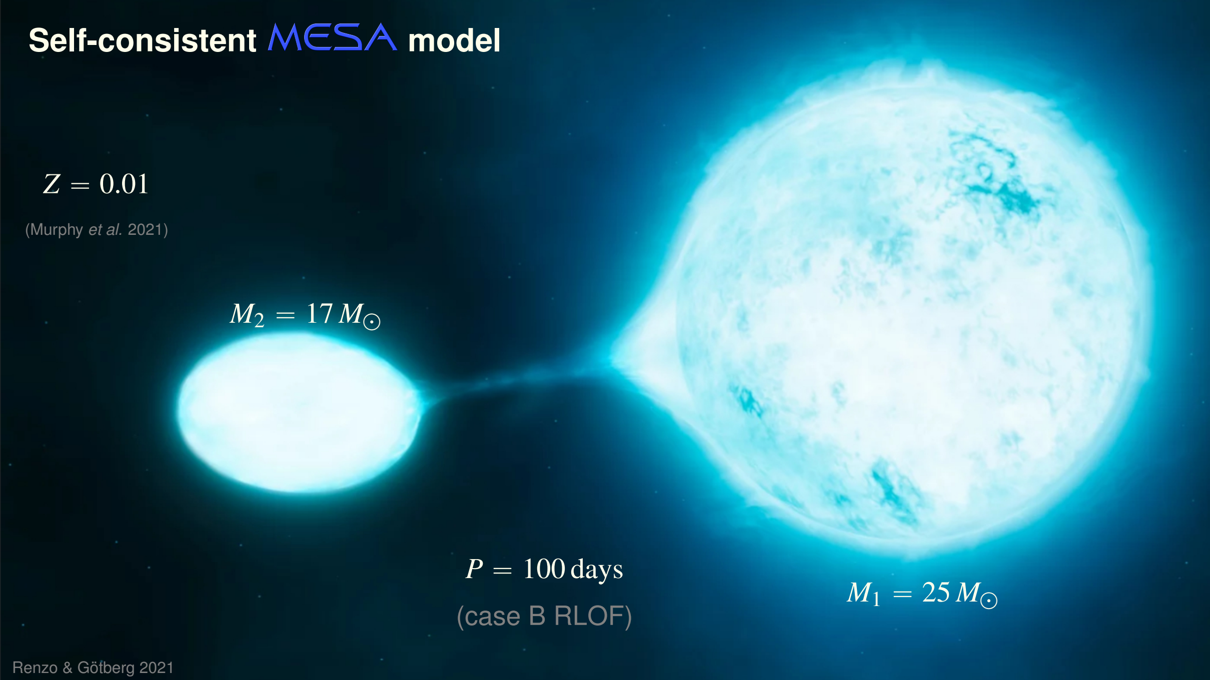
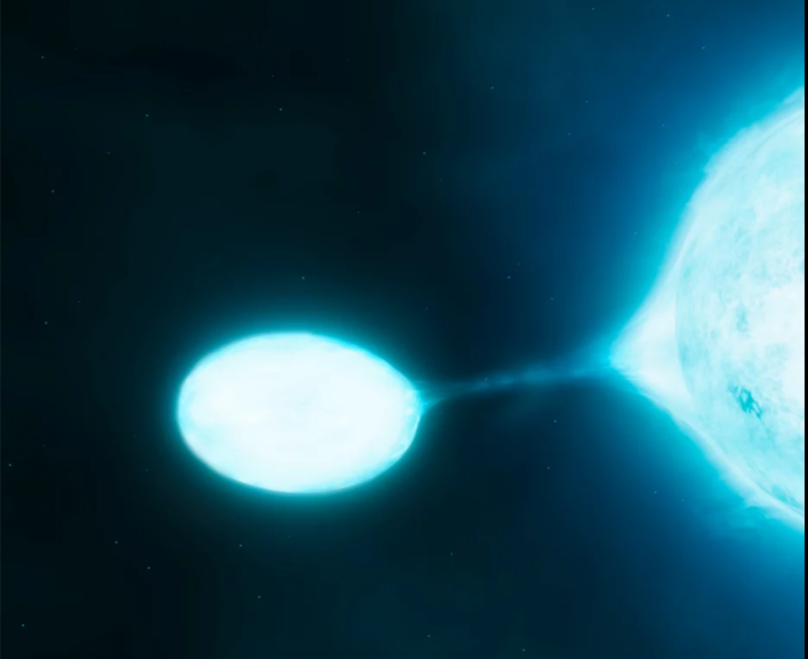
Renzo *et al.* 19b

Self-consistent MESA model





Not simultaneous!

Not simultaneous!

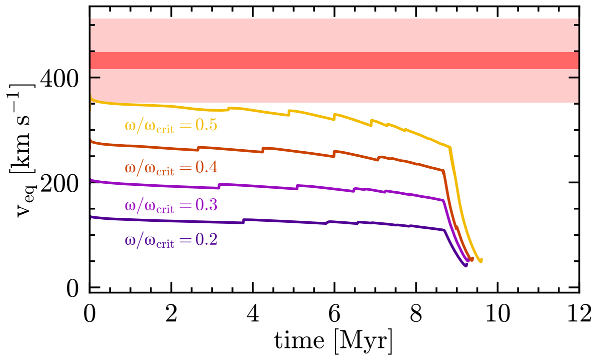
Does a binary past help with ζ Oph. ?

Spin-up – Pollution – Rejuvenation

Renzo & Götberg 2021

✗ Spin up:

Natal rotation would need to be extreme to match

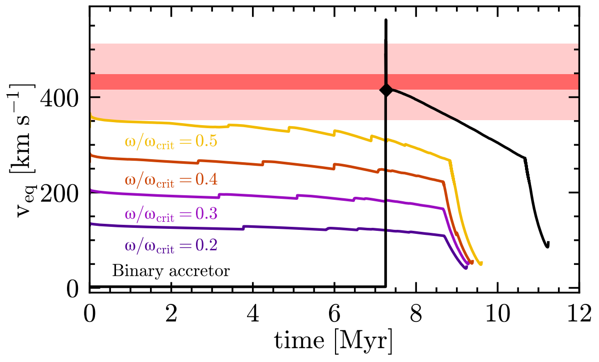


weak-wind problem, neglecting inclination

Renzo & Götberg 2021

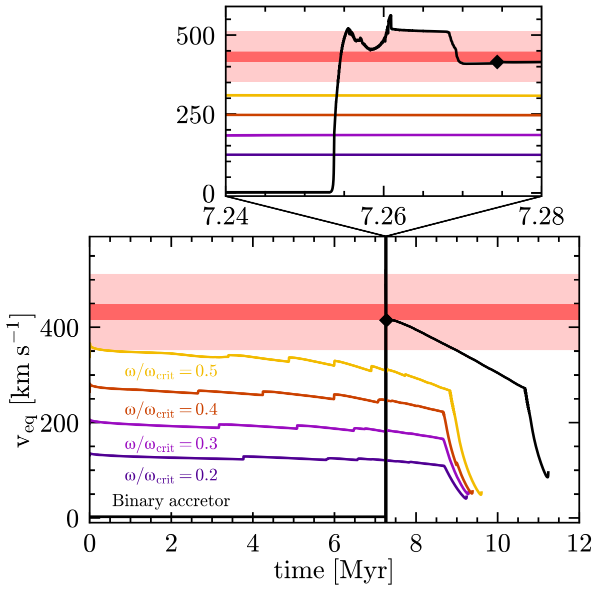
✓ Spin up:

late and to critical rotation



weak-wind problem, neglecting inclination

Renzo & Götberg 2021

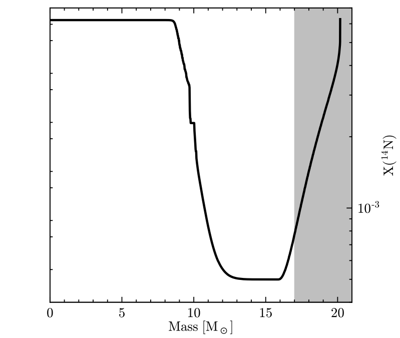


weak-wind problem, neglecting inclination

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core



Nitrogen mass fraction

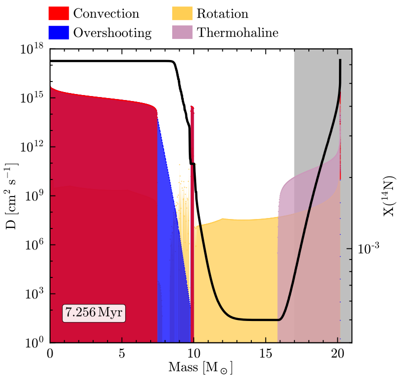
Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core

"Mixing strength"



Nitrogen mass fraction

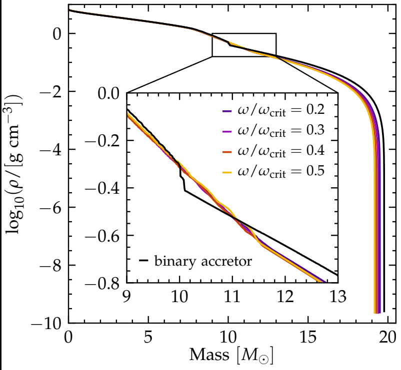
Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Rejuvenation:

Core growth changes its outer boundary

“Density”



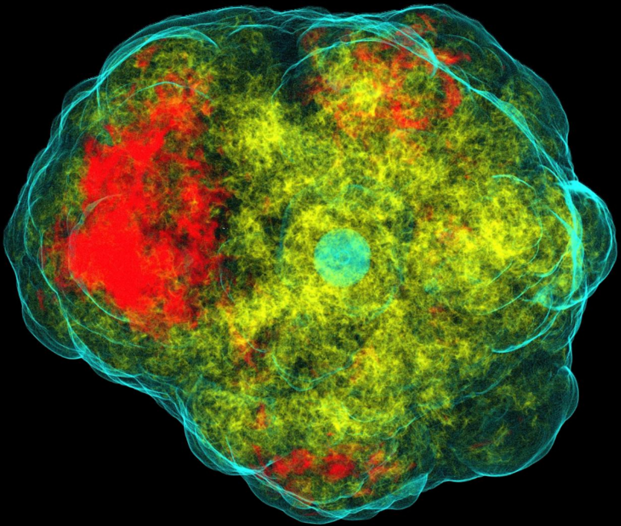
end of H-core burning,
later evolution amplifies differences

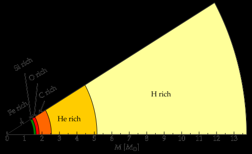
(e.g., Renzo *et al.* 2017)

Renzo & Götberg 2021, Renzo *et al.* 2023

Asymmetries in the explosion cause the "kick"

- ν-driven convection
- rotation
- hydrodynamical flow





Credits: S. Drasco

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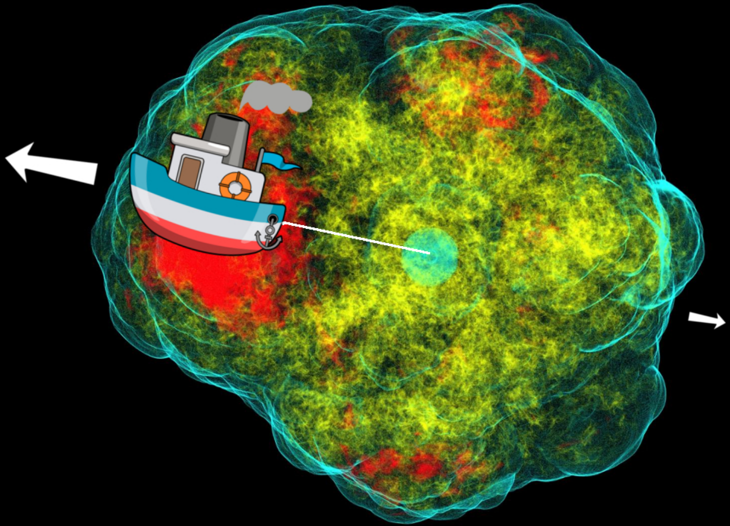

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